

California Department of Transportation
Division of Environmental Analysis
Office of Noise, Air Quality, and Hazardous Waste Management
Sacramento, CA

TRANSPORTATION RELATED EARTHBORNE VIBRATIONS

(Caltrans Experiences)

Technical Advisory, Vibration
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NOTICE:

This document is a revision of technical advisory TAV-96-01-R9201 with the same title, prepared by the same author, dated June 13, 1996. This revision does not alter the basic information of the earlier version, except for the Rayleigh wave propagation equation (see eq.1 and associated eq.2), which was in error and has been corrected. The text associated with the equation as well as the text in figure 1 has also been changed. The error did not affect the vibration dropoff curve in figure 1. Some other changes were made in formatting and wording.

This document is not an official policy, standard, specification or regulation and should not be used as such. Its contents are for informational purposes only. Any views expressed in this advisory reflect those of the author, who is also responsible for the accuracy of facts and data presented herein. The latter were derived from Caltrans vibration studies from 1958 to 1994, and the author's vibration experiences from 1980 to 1994 at the Caltrans Transportation Laboratory (Translab) in Sacramento, CA.

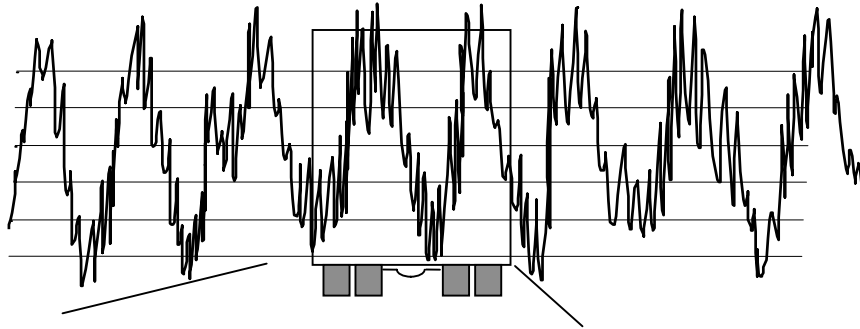


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INTRODUCTION

This Technical Advisory is intended to give district environmental, materials, design, construction and other concerned personnel a basic understanding of transportation related earthborne vibrations. The advisory covers general vibration principles, vibrations caused by construction and operation of transportation facilities, criteria used by the California Department of Transportation (Caltrans), impacts, vibration study approaches, possible mitigation, and screening procedures to identify potential vibration problems in the field.

District personnel are usually the first to be contacted by the public when vibration problems occur. Until 1994, the district personnel in turn contacted the Caltrans laboratory (TransLab) and requested either an assesment of the problem or a vibration field study. In 1994, Translab discontinued the field studies because of a reorganization. Presently, HQ Division of Environmental Analysis, Noise, Air Quality and Hazardous Waste Management Office, Noise and Vibration Branch is responsible for providing guidance on potential vibration problems.

The information in this advisory will enable district personnel to participate in assessing and screening routine vibration complaints as well as provide background information for the oversight of more complex studies. This advisory will also be a useful source of information for developing contract specifications and oversight.

BACKGROUND

Caltrans has performed earthborne vibration studies since 1958. In 1976, a landmark TransLab vibration research report titled "Survey of Earth-borne Vibrations due to Highway Construction and Highway Traffic", Report No. CA-DOT-TL-6391-1-76-20, compiled a summary of results, findings, and conclusions of 23 studies completed in the 17 year period between 1958 and 1975. Since then many more studies have been performed. Most of these fall into the following three categories:

- Highway traffic vibrations
- Construction vibrations
- Train/light rail vibrations

The main concerns of vibrations involve:

- Annoyance
- Damage
- Disruption of vibration sensitive operations or activities
- Triggering of land slides

The sites investigated included private residences, factories, aerospace and defense plants, electronic laboratories, radio station, movie studio, etc., and even a major cake and pastry bakery.

Because of similarities between the disciplines of noise and vibrations, the former Noise Section took over the responsibilities for vibration studies from the Electrical Instrumentation Testing and Research Section in July, 1980. Almost two-thirds of the above mentioned studies were performed by the Noise Section, which, in 1994 was absorbed by the newly created Office of Environmental Engineering of the Environmental Program. The individual study reports are on file at the Office of Environmental Engineering. This advisory incorporates information and experience gained in all Caltrans vibration studies from 1958-1994.

FUNDAMENTALS OF EARTHBORNE VIBRATIONS

Vibration Sources

Sources of earthborne vibrations include natural phenomena (earthquakes, volcanic eruptions, sea waves, landslides, etc.), or manmade causes (explosions, machinery, traffic, trains, construction equipment, etc.). Vibration sources may be continuous such as factory machinery, and transient, such as explosions.

A distinction must be made between earthborne and airborne vibrations. Some sources, such as jet aircraft, rockets, explosions, sonic booms, locomotives, and even trucks under certain conditions, can create low frequency airborne noise of enough intensity to be felt, as well as heard. These low frequency airborne blasts or rumbles are often erroneously perceived as earthborne vibrations.

As is the case with airborne sound, earthborne vibrations may be described by amplitude and frequency.

Amplitude and Frequency

In airborne sound, amplitude is described by common logarithm of the square of the ratio of pressure fluctuations around mean air pressure divided by a reference pressure, and is expressed in logarithmic units of decibels. The pressure fluctuations propagate in waves of alternating compressed and rarefied air. The rate at which these waves radiate outward from their source is called the speed of sound, which is the wave velocity. Air is an elastic medium through which the waves travel.

In earthborne vibrations, amplitude is described by the local movement of soil particles. This movement must not be confused with wave velocity.

To distinguish between wave velocity and particle motion, consider the analogy of ripples on a lake and a floating cork. Wave velocity (in air, speed of sound) is analogous to the velocity of the ripples. Particle motion may be compared to the bobbing of the cork as the ripples pass by. The bobbing of the cork represents the local movement of the soil particles as earthborne vibration waves pass through the soil. The soil acts as an elastic medium.

The amplitude of particle motion may be described three ways:

1. **Particle displacement** - the distance the soil particles travel from their original position. Units are millimeters (mm), inches (in)
2. **Particle velocity** - the velocity of the soil particles. Units are inches per second (in/sec) or millimeters per second (mm/sec). Sometimes expressed logarithmically in decibels (dB) with reference to a specified unit of velocity such as .001 in/sec, or 0.001 mm/sec.
3. **Particle acceleration** - the acceleration of the soil particles. Units are inches per second per second (in/sec²), millimeters per second per second (mm/sec²), or g-force (g = acceleration of gravity = 32.2 feet per second per second (ft/sec²) = 9.81 meter per second per second (m/sec²). Sometimes expressed logarithmically in decibels (dB) with reference to a specified unit of acceleration, such as 1 g, or 0.001g.

For a perfect sine wave produced by a single vibration frequency there exists a simple relationship between the above three measures of amplitude (see Appendix). If the frequency and amplitude of one descriptor is known, the other two can easily be calculated. For waves consisting of many frequencies, and therefore not sine waves, the relationships become much more complicated.

There is a 90 degree phase shift between the three descriptors, i.e. velocity is 90 degrees out of phase with displacement, acceleration is 90 degrees out of phase with velocity, and acceleration is 180 degrees out of phase with displacement. To illustrate this, we might imagine a pendulum just released from a point furthest away from its stationary position. If we arbitrarily call this position the extreme positive (+) position of the pendulum, the stationary point 0, and the region beyond the stationary point a negative (-) position, we observe the following:

- at the point of release, the displacement (distance from stationary or 0 displacement position) is maximum and positive (+).
- the velocity at the point of release is 0.
- the acceleration at the point of release is at its maximum, in the direction towards the negative (-).

This can be worked out the same for other pendulum positions. For instance, as the pendulum swings through the stationary position, the displacement is 0, the velocity is maximum in the negative (-) direction, and the acceleration is 0. Once past the

stationary point the pendulum decelerates in the negative (-) direction which is the same as increasing acceleration in the positive (+) direction.

Vibration amplitudes are usually expressed as either "peak", as in peak particle velocity, or "rms" (root mean square), as in rms acceleration. The relationship between the two is the same as with noise. The rms value is approximately 0.71 x the peak value for a sine wave representing either displacement, velocity, or acceleration.

Finally, the direction in which vibrations are measured, analyzed or reported should be specified (vertical, horizontal longitudinal, horizontal transverse, or the resultant of all three motions). For example, Caltrans most often uses a peak vertical particle velocity descriptor, because vibrations along the ground surface are most often (although not always) greatest in the vertical direction.

Propagation

Propagation of earthborne vibrations is complicated because of the endless variations in the soil through which waves propagate.

The relationship between frequency (**f**), period (**T**), wave length (**λ**), and wave velocity (**c**) is the same as that in noise, that is:

$$f=1/T \text{ and } f=c/\lambda$$

However, the wave velocity (c, sometimes also called the phase velocity) in soils varies much more than the speed of airborne sound does, and is often also frequency dependent (the speed of sound only varies with temperature). As a consequence, wavelength cannot readily be calculated when frequency is known and vice versa, unless the wave velocity happens to be known also.

There are three main wave types of concern in the propagation of earthborne vibrations:

1. **Surface or Rayleigh waves**, which as the name implies, travel along the ground surface. They carry most of their energy along an expanding cylindrical wave front, similar to the ripples produced by throwing a rock into a lake. The particle motion is retrograde elliptical, more or less perpendicular to the direction of propagation.
2. **P-waves, or compression waves**. These are body waves that carry their energy along an expanding spherical wave front. The particle motion in these waves is longitudinal, "push-pull". P-waves are analogous to airborne sound waves.
3. **S-waves, or shear waves**. These are also body waves, carrying their energy along an expanding spherical wave front. Unlike P-waves, however, the particle motion is transverse, or perpendicular to the direction of propagation.

As wave fronts move outward from a vibration source, their energy is spread over an ever increasing area. The more rapidly this area increases, the more quickly the energy intensity (energy per unit area) decreases. The areas of cylindrical Raleigh wave fronts

do not increase as rapidly with distance as do the body (P- and S-) waves. Consequently, the energy intensities of Raleigh waves attenuate at a lesser rate with distance than those of body waves.

The spreading of energy over ever increasing areas is called geometric spreading (geometric attenuation) and the difference in attenuation rates between surface and body waves is analogous to that of line sources and point sources, respectively, in airborne sound. Geometric attenuation also results of encountering more soil mass as the area of the wave front increases.

Geometric attenuation is not the only attenuation encountered with distance. Hysteretic attenuation, or material damping, results from energy losses due to internal friction, soil layering, voids, etc. The amount of hysteretic attenuation varies with soil type, condition, and frequency of the source.

These variations make it much more difficult to predict vibration levels at specific locations, than it is to predict noise levels.

In general, manmade earthborne vibrations attenuate rapidly with distance from the source. Even the more persistent Rayleigh waves decrease relatively quickly. Manmade vibration problems are therefore confined to short distances from the source.

In contrast, natural vibration problems are often wide spread. An obvious example is an earthquake which can cause damage over large areas, due to the release of enormous quantities of energy.

TRANSPORTATION RELATED EARTHBORNE VIBRATIONS

Sources

Caltrans is most commonly concerned with three types of transportation related earthborne vibration sources:

- Normal highway traffic - heavy trucks, and quite frequently buses, generate the highest earthborne vibrations of normal traffic. Vibrations from these vary with pavement conditions. Pot holes, pavement joints, differential settlement of pavement, etc., all increase the vibration levels.
- Construction equipment - pile driving, pavement breaking, blasting, and demolition of structures generate among the highest construction vibrations.
- Heavy and light rail operations - diesel locomotives, heavily loaded freight cars, and operations such as coupling create the highest rail traffic vibrations.

Of the above three types, construction vibrations are of greatest concern. The four operations mentioned under construction vibrations are potentially damaging to buildings at distances of less than 7.5 m (25 ft) from the source.

Descriptor Used By Caltrans

With the exception of some construction operations such as pile driving, pile hole drilling, and perhaps some deep excavations, all vibrations generated by construction or operation of surface transportation facilities are mainly in the form of surface or Raleigh waves. Studies have shown that the vertical components of transportation generated vibrations are the strongest and that peak particle velocity correlates best with damage and complaints. For these reasons, Caltrans adopted the Peak Vertical Particle Velocity descriptor, with units of mm/sec or in/sec.

A great advantage of using this descriptor is that for a frequency range of 1 - 80 Hz damage levels in terms of velocity tend to be independent of frequency. The same is true for complaint levels within a range of 8 - 80 Hz. Velocity is the product of frequency, displacement and a constant (see appendix). It appears that within the above frequency ranges a doubling of frequency will offset a halving of displacement and vice versa; i.e. the effects of the product of the two tend to remain equal. Typical transportation and construction vibrations fall within the above frequency ranges. They typically range from 10 - 30 Hz, and usually center around 15 Hz.

From the above we can surmise that not only the effects of displacement are frequency dependent, but also those of acceleration. The latter is related to the former by the frequency times a constant squared (see appendix). Thus, criteria levels in terms of displacement or acceleration need to be accompanied by a frequency.

Propagation of Transportation Related Vibration

Raleigh (Surface) Wave Drop-off - Surface waves generated by traffic, trains, and most construction operations tend to attenuate with distance according to the following equation:

$$V = V_0(D_0/D)^{0.5} e^{\alpha(D_0-D)} \quad (\text{eq. 1})$$

where: V = Peak particle velocity at distance D
 V_0 = Peak particle velocity at reference distance D_0
 D_0 = Reference distance
 D = Distance for which vibration level needs to be calculated
 e = Base of natural logarithm = 2.718281828
 α = Soil parameter

The soil parameter α can be determined by simultaneous vibration measurements at a minimum of two different distances from a source. One distance should be near the source, ideally between 4.5 and 7.5 m (15 -25 ft). The other should be farther away from the source, ideally at or beyond the farthest point of interest, but at a location where the source is still measurable and not contaminated by other vibrations. A third

point in between is recommended for confirmation. Note that the value of α depends on the distance units used. The reason for this is that the exponential $(D_0 - D)$ α needs to be a constant value while the value of $(D_0 - D)$ changes with the units used (normally, m or ft). Therefore, the relationship between α (based on m) and α (based on ft) is:

$$\begin{aligned}\alpha \text{ (based on m)} &= 3.281 \alpha \text{ (based on ft), and} \\ \alpha \text{ (based on ft)} &= 0.305 \alpha \text{ (based on m)}\end{aligned}$$

α can be calculated from the vibration measurements by rewriting eq. 1 as:

$$\alpha = (\ln V^2 + \ln D - \ln V_0^2 - \ln D_0) / 2(D_0 - D) \quad (\text{eq. 2})$$

where "ln" denotes "natural logarithm"

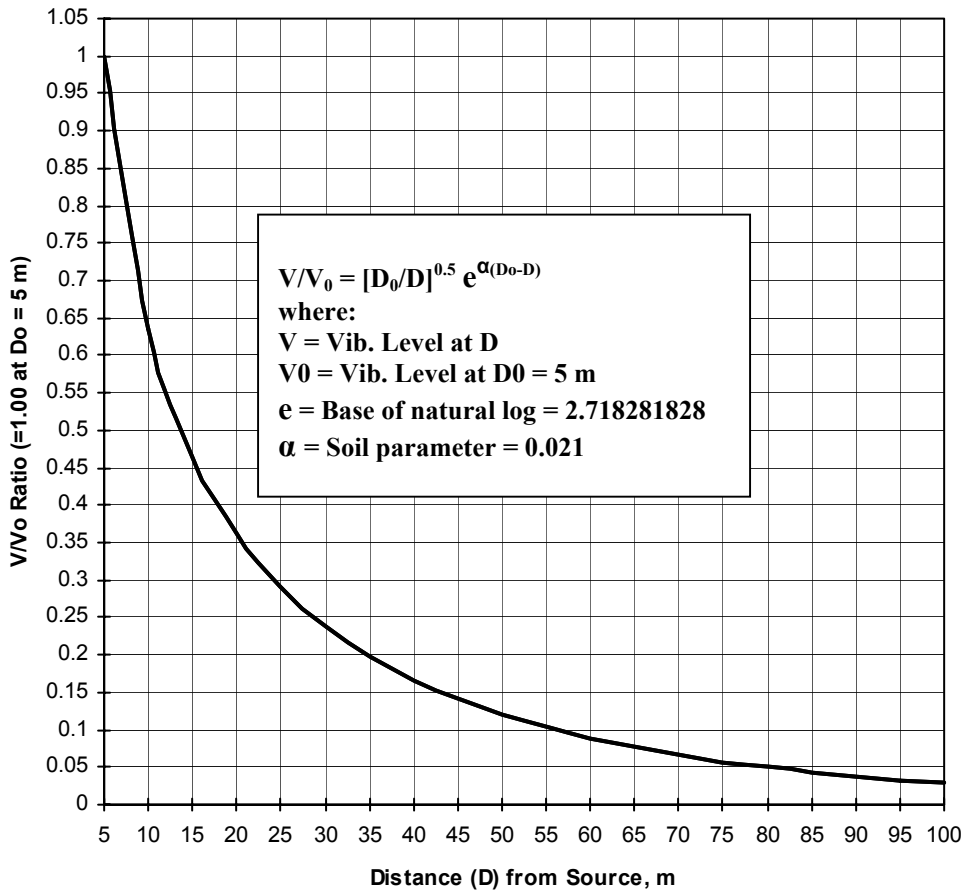
Once α is calculated from the measurements it can be used in eq. 1 to calculate vibrations for any other distance, given the same reference source.

Figure 1 shows a drop-off curve expressed as a ratio of V/V_0 , using a reference distance D_0 of 5 m (16 ft). This is a normalized curve for $\alpha = \mathbf{0.021}$ (distance in m), or $\alpha = \mathbf{0.006}$ (distance in ft), derived from data measured in the City of Lynwood to calculate α for the LA-105 Alameda Viaduct vibration study, involving traffic effects on Westech Gear Corporation (formerly Western Gear) close tolerance manufacturing operations. The attenuation curve in Figure 1 is valid for the soils stratification derived from Caltrans boring logs for the Alameda Viaduct, shown in Table 1.

Table 1. - Soils Classifictaions for Figure 1.

Depth, m (ft)	Soil Description
0	
	<i>Sand-Silt</i>
1.5 (5)	
	<i>Clayey Silt</i>
9 (29)	
	<i>Silty Sand</i>
12 (40)	
	<i>Sandy Silt</i>
15.5 (51)	
	<i>Sand</i>
19.5 (64)	

Figure 1. Typical Normalized Distance Attenuation Ratio Curve of Earthborne Surface Vibrations (Reference Distance, $D_0 = 5$ m)



The curve is representative of many locations in the L.A. Basin, and also of various locations in Sacramento, and can be used for estimating traffic, train, and most construction vibration drop-offs with distance. To use the curve, the vibration level V_1 must be known at a given distance D_1 near the source, preferably between 5 and 15 m (16 and 50 ft). The vibration level V_2 at the distance of interest D_2 can then be calculated as follows:

$$V_2 = (V_2/V_0) / (V_1/V_0) \cdot V_1$$

(the ratio's V_2/V_0 and V_1/V_0 can be obtained from Figure 1)

For example, if the vibration level is known to be 3.2 mm/s (peak particle velocity) at a distance of 12 m, the vibration level at 58 m can be estimated from $(0.09/0.55) \times 3.2$ mm/s = 0.5 mm/s.

Pile Driving Vibration Drop-off - During pile driving, vibration levels near the source depend mainly on the soil's penetration resistance. In soils such as sand and silt, this resistance is relatively low with the result that a large portion of the impact energy is used to advance the pile. Less energy is then available for generating ground vibrations. In clay soils, however, the penetration resistance is higher and more energy is available for ground vibrations. The resistance provided by the soils consists of friction along the sides of the pile as well as compressional resistance due to the transfer of energy of the pile tip to the soil. This appears to generate body waves as opposed to surface waves by other construction operations.

The energy of a pile driver is of course also influential on the vibration level at the source. There is a relationship between vibration level and energy. If pile driver energy changes from E_1 to E_2 , the vibration level at a certain location changes from V_1 to V_2 , where:

$$V_2 = V_1 \left(\sqrt{\frac{E_2}{E_1}} \right) \quad \text{(Eq. 3)}$$

Example: $E_1 = 68,000$ J (50,000 ft lbf)

$E_2 = 111,900$ J (82,500 ft lbf)

$V_1 = 2.8$ mm/s

Then: $V_2 = 2.8 \left(\sqrt{\frac{111,900}{68,000}} \right) = 3.6$ mm/sec

Vibrations of pile driving appear to drop off differently than the Raleigh waves, probably due to the presence of a significant proportion of body waves. Pile driving vibrations tend to drop off with distance according to the following equation:

$$V = V_0 \cdot (D_0/D)^k \quad \text{(Eq. 4)}$$

where: V , V_0 , D_0 , and D are same as defined in Eq. 1, and
 k = soil parameter (no units)

(Note that α and k are different parameters; whereas the value of α is dependent on the distance units used (m or ft), the value of k - which depends only on the ratio of distances - is independent of distance units used.)

Generally, the values of "k" lie between 1 to 1.5 (approaching 1 for sandy soils and 1.5 for clay soils), although values > 1 and < 1.5 have been encountered.

The value of "k" can be determined experimentally at different distances from a pile driver, similarly to the previously described derivation of α . For this purpose, Eq. 4 can be rewritten as:

$$k = (\text{Log}V - \text{Log}V_0)/(\text{Log} D_0 - \text{Log}D) \quad (\text{eq. 5})$$

Caltrans Vibration Criteria

There are no FHWA or state standards for vibrations. The traditional view has been that highway traffic and construction vibrations pose no threat to buildings and structures, and that annoyance to people is no worse than other discomforts experienced from living near highways.

Damage - A considerable amount of research has been done to correlate vibrations from single events such as dynamite blasts with architectural and structural damage. The U.S. Bureau of Mines has set a "safe blasting limit" of 50 mm/s (2 in/sec). Below this level there is virtually no risk of buiding damage.

"Safe" levels for continuous vibrations from sources such as traffic are not as well defined. The Transport and Road Research Laboratory in England has researched continuous vibrations to some extent and developed a summary of vibration levels and reactions of people and the effects on buildings (Table 2). These are the criteria used by Caltrans to evaluate the severity of vibration problems. Traffic, train, and most construction vibrations (with the exception of pile driving, blasting, and some other types of construction/demolition) are considered continuous. The "architectural damage risk level" for continuous vibrations (peak vertical particle velocity of 5 mm/sec or 0.2 in/sec) shown in Table 2 is one tenth of the maximum "safe" level of 50 mm/sec (2 in/sec) for single events.

All damage criteria for buildings are in terms of ground motion at the buildings' foundations. No allowance is included for the amplifying effects of structural components. Obviously, the way a building is constructed and the condition it is in determines how much vibration it can withstand before damage appears. Table 2 shows a recommended upper level of 2.0 mm/s (0.08 in/sec) for continuous vibrations to which "ruins and ancient monuments" should be subjected. This criterion level may also be used for historical buildings, or buildings that are in poor condition.

Relatively little information is available concerning the damaging effects of pile driving. Although technically a series of single events, pile driver blows occuring often enough in

a confined area could cause damage at a lower level than the single event criterion of 50 mm/s (2 in/sec). Caltrans has experienced some minor damage from sustained

**Table 2 - Reaction of People and Damage to Buildings
at Various Continuous Vibration Levels**

Vibration Level (Peak Particle Velocity)*		Human Reaction	Effect on Buildings
mm/s	in/sec		
0.15-0.30	0.006-0.019	Threshold of perception; possibility of intrusion	Vibrations unlikely to cause damage of any type
2.0	0.08	Vibrations readily perceptible	Recommended upper level of the vibration to which ruins and ancient monuments should be subjected
2.5	0.10	Level at which continuous vibrations begin to annoy people	Virtually no risk of “architectural” damage to normal buildings
5.0	0.20	Vibrations annoying to people in buildings (this agrees with the levels established for people standing on bridges and subjected to relative short periods of vibrations)	Threshold at which there is a risk of “architectural” damage to normal dwelling - houses with plastered walls and ceilings Special types of finish such as lining of walls, flexible ceiling treatment, etc., would minimize “architectural” damage
10-15	0.4-0.6	Vibrations considered unpleasant by people subjected to continuous vibrations and unacceptable to some people walking on bridges	Vibrations at a greater level than normally expected from traffic, but would cause “architectural” damage and possibly minor structural damage.

* The vibration levels are based on peak particle velocity in the vertical direction. Where human reactions are concerned, the value is at the point at which the person is situated. For buildings, the value refers to the ground motion. No allowance is included for the amplifying effect, if any, of structural components.

Source: “A Survey of Traffic-induced Vibrations” by Whiffen and Leonard, Transport and Road Research Laboratory, RRL Report LR418, Crowthorne, Berkshire, England, 1971.

pile driving at about 7.5 - 9 mm/s (0.30 - 0.35 in/sec) peak vertical particle velocity vibration level on the ground next to an existing parking structure. The extent of the damage was some crumbling of mortar used to fill wall joints. In that instance the distance to the pile driving was slightly greater than 5 m (17 ft). The pile driver energy and the soil conditions were unknown. It is likely that the ground vibrations were amplified by the structure, causing the damage.

On the whole, the architectural damage criterion for continuous vibrations, 5 mm/s (0.2 in/sec) appears to be conservative even for sustained pile driving. Pile driving levels often exceed 5 mm/s (0.2 in/sec) at distances of 15 m (50 ft), and 13 mm/s (0.5 in/sec) at 7.5 m (25 ft). Pile driving has been done frequently at these distances without apparent damage to buildings (with the previously mentioned exception). The criterion level for pile driving is therefore somewhere between 5 and 50 mm/s (0.2 and 2 in/sec). The 50 mm/s (2 in/sec) single event criterion is still being used by some organizations and engineering firms as a safe level for pile driving. Although never measured by Caltrans, calculations show that this level will be probably exceeded within 2 m (6 ft) from a 68,000 J (50,000 ft lbf) pile driver. This level is probably a "safe" criterion to use for well engineered and reinforced structures. For normal dwellings, however, pile driving peaks should probably not be allowed to exceed 7.5 mm/s (0.3 in/sec). In any case, **extreme care must be taken when sustained pile driving occurs within 7.5 m (25 ft) of any building, and 15-30 m (50-100 ft) of a historical building, or building in poor condition.**

When high levels of construction vibrations (such as from pile driving, demolition, and pavement breaking) are expected at residences or other buildings, it is recommended that a detailed "crack survey" be undertaken BEFORE the start of construction activities. The survey may be done by photographs, video tape, or visual inventory, and should include inside as well as outside locations. All existing cracks in walls, floors, driveways, etc. should be documented with sufficient detail for comparison after construction to determine whether actual vibration damage has occurred.

Annoyance - The annoyance levels in Table 2 should be interpreted with care. Depending on the activity (or inactivity) a person is engaged in, vibrations may be annoying at much lower levels than those shown in Table 2. Elderly, retired, or ill people staying mostly at home, people reading in a quiet environment, people involved in vibration sensitive hobbies or other activities are but a few examples of people that are potentially annoyed by much lower vibration levels. Most routine complaints of traffic vibrations come from people in these categories. To them, even vibrations near the threshold of perception may be annoying.

Frequently, low level traffic vibrations can cause irritating secondary vibrations, such as a slight rattling of doors, windows, stacked dishes, etc. These objects are often in a state of neutral equilibrium and readily respond to very low levels of vibrations. The rattling sound gives rise to exaggerated vibration complaints, even though there is very little risk of damage.

Other criteria - At times, other criteria may be necessary to address very specific concerns. For example, vibration sensitive manufacturing or calibration processes, such as close tolerance machining, laboratories calibrating sensitive electronic equipment, use of electron microscopes, etc. often require vibration criteria that are much lower than the threshold of perception level.

Determining the specific criterion level for such sites is no easy task, and requires the cooperation of the engineers, technicians, or managers involved with the operations. Frequently, even those experts do not know at what level of vibrations their operations will be disturbed, and tests involving generation of vibrations (such as running a heavy truck over 2"x4" wooden boards outside the plant), vibration monitoring equipment, and a test operation must be performed.

Typical Traffic Vibration Levels

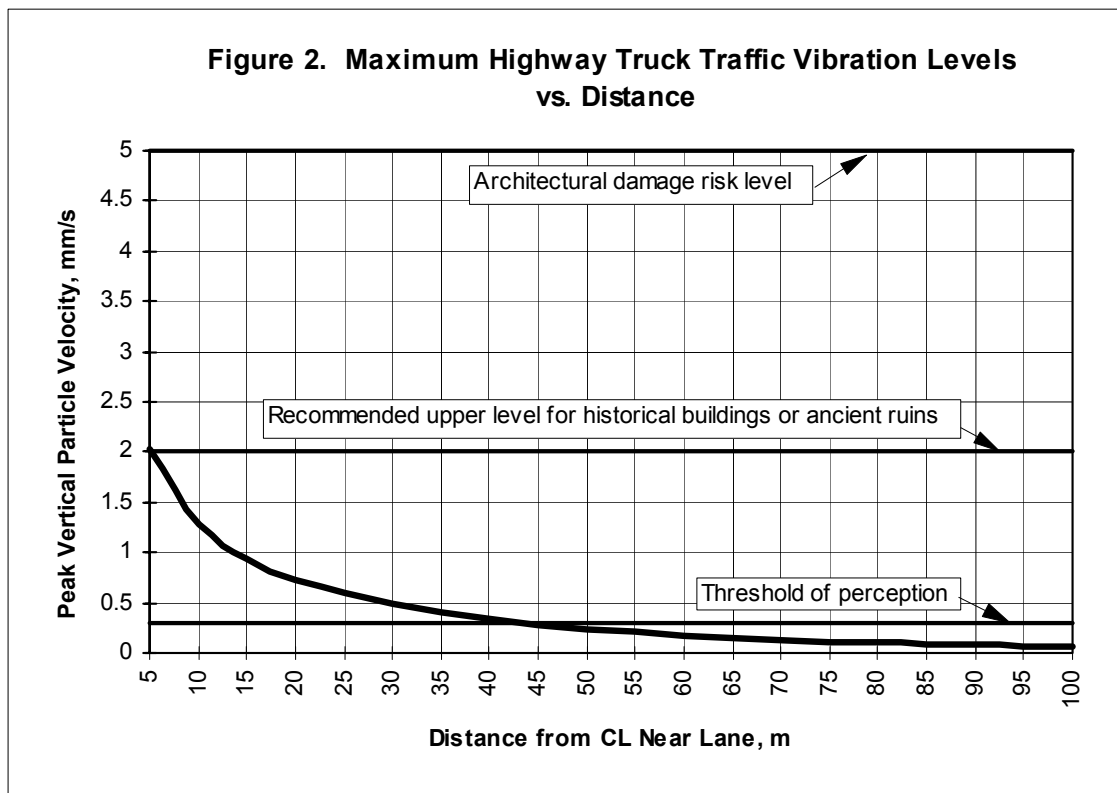
From Figure 1 typical relationships of traffic vibrations vs. distance from a freeway can be developed. For instance, vibration data of truck passbys are characterized by peaks that are considerably higher than those generated by automobiles. These peaks last no more than a few seconds and often only a fraction of a second, indicating a rapid drop-off with distance. Figure 1 showed that at 15 m (50 ft) from the centerline of the nearest lane, truck vibrations are about half of those measured near the edge of shoulder (5 m, or about 15 ft from the centerline of the near lane). At 30 m (100 ft) they are about one fourth, at 60 m (200 ft) about one tenth, and at 90 m (300 ft) less than one twentieth. These rough estimates are supported by years of measurements throughout California.

Because of the rapid dropoffs with distance, even trucks traveling close together often do not increase peak vibration levels substantially. In general, more trucks will show up as more peaks, not necessarily higher peaks. Wavefronts emanating from several trucks closely together may either cancel or partially cancel (**destructive interference**), or reinforce or partially reinforce (**constructive interference**) each other, depending on their phases and frequencies. Since traffic vibrations can be considered random, the probabilities of total destructive or constructive interference are extremely small. Coupled with the fact that two trucks cannot occupy the same space, and the rapid drop-off rates, it is understandable that two or more trucks normally do not contribute significantly to each other's peaks. It is, however, good practice to try and include the worst combinations of truck clusters with heavy loads in traffic passby vibration measurements. This obviously requires a good view of the traffic, or an observer who is in communication with the instrument operator.

Figure 2 is a plot of maximum highway truck traffic vibrations vs. distance from the centerline of the nearest freeway lane. The curve was compiled from the highest measured vibrations available from previous studies. Some of the Table 2 criteria are also plotted, for comparison. The graph indicates that the highest traffic generated vibrations measured on freeway shoulders (5 m from center line of nearest lane) have never exceeded 2.0 mm/s, with worst combinations of heavy trucks. This level coincides with the maximum recommended “safe level” for ruins and ancient monuments (and historical buildings). The graph illustrates the rapid attenuation of vibration levels, which dip below the threshold of perception for most people at about 45 m (150 ft).

Automobile traffic normally generates vibration peaks of one fifth to one tenth of truck vibrations.

Traffic vibrations generally range in frequencies from 10-30 Hz, and tend to center around 15 Hz. However, it is not uncommon to measure lower frequencies, even down to 1-2 Hz. Due to their suspension systems, city buses often generate frequencies around 3 Hz, with high velocities (indicating high displacements). It is more uncommon, but possible, to measure frequencies above 30 Hz.



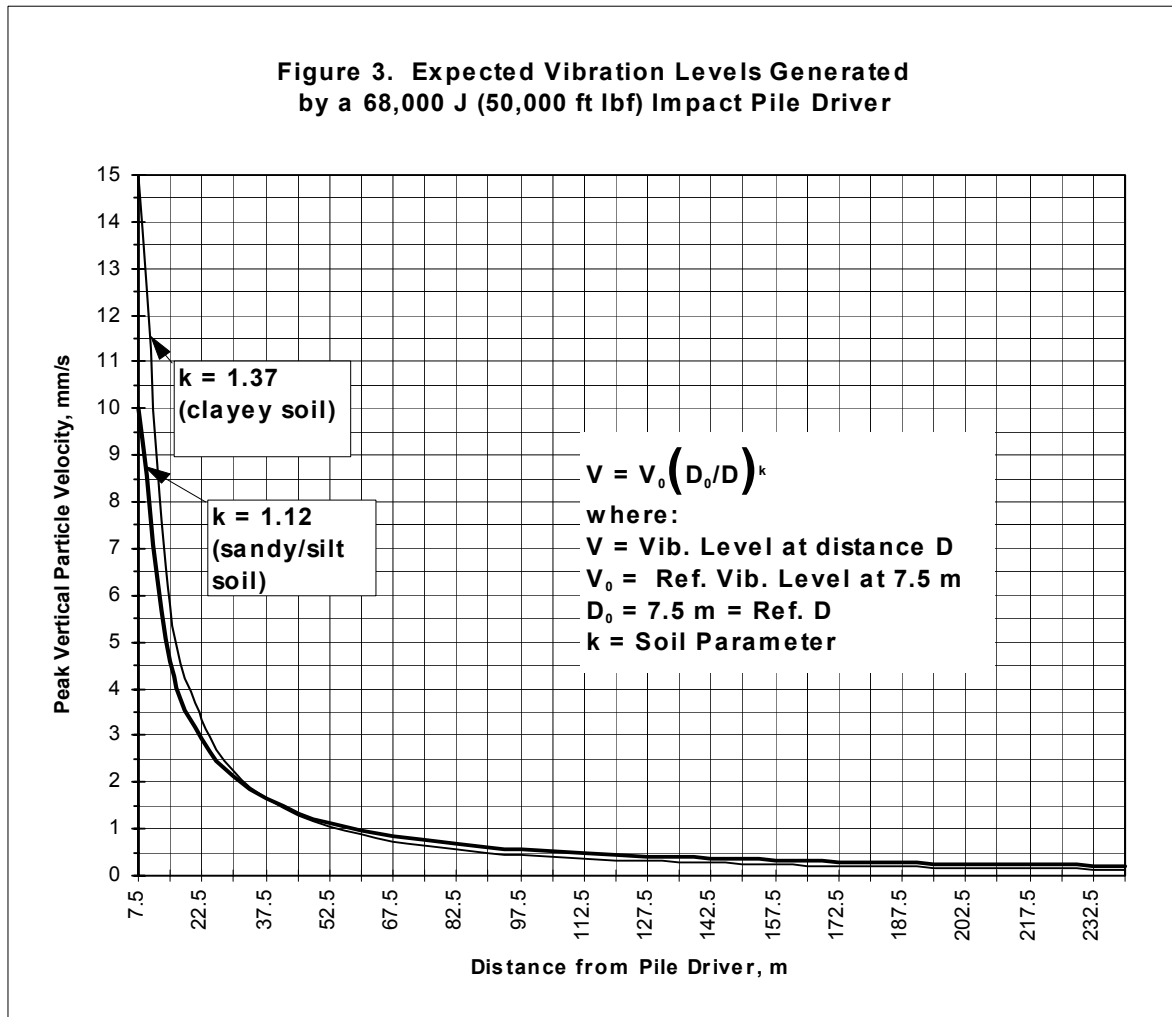
Construction Vibration Levels

With the exception of a few instances involving pavement breaking, pile driving, all Caltrans construction vibration measurements have been below the 5 mm/s (0.2 in/sec) architectural damage risk level for continuous vibrations. The highest measured vibration level was 73.1 mm/s (2.88 in/sec) at 3 m (10 ft) from a pavement breaker. This instance marked the only time that the single event safe level of 50 mm/s (2 in/sec) was exceeded during vibration monitoring by Caltrans.

Other construction activities and equipment, such as D-8 and D-9 Caterpillars, earthmovers and haul trucks have never exceeded 2.5 mm/s (0.10 in/sec) or one half of the architectural damage risk level, at 3 m (10 ft)). Depending on the activity and the source, construction vibrations vary much more than traffic vibrations.

Figure 3 shows typical pile driving vibrations with distance, for a 68,000 J (50,000 ft lbf) energy impact pile driver, for two different soils (clayey and sandy with silt). Clay

soils provide more resistance to advancing piles and therefore generate higher vibration

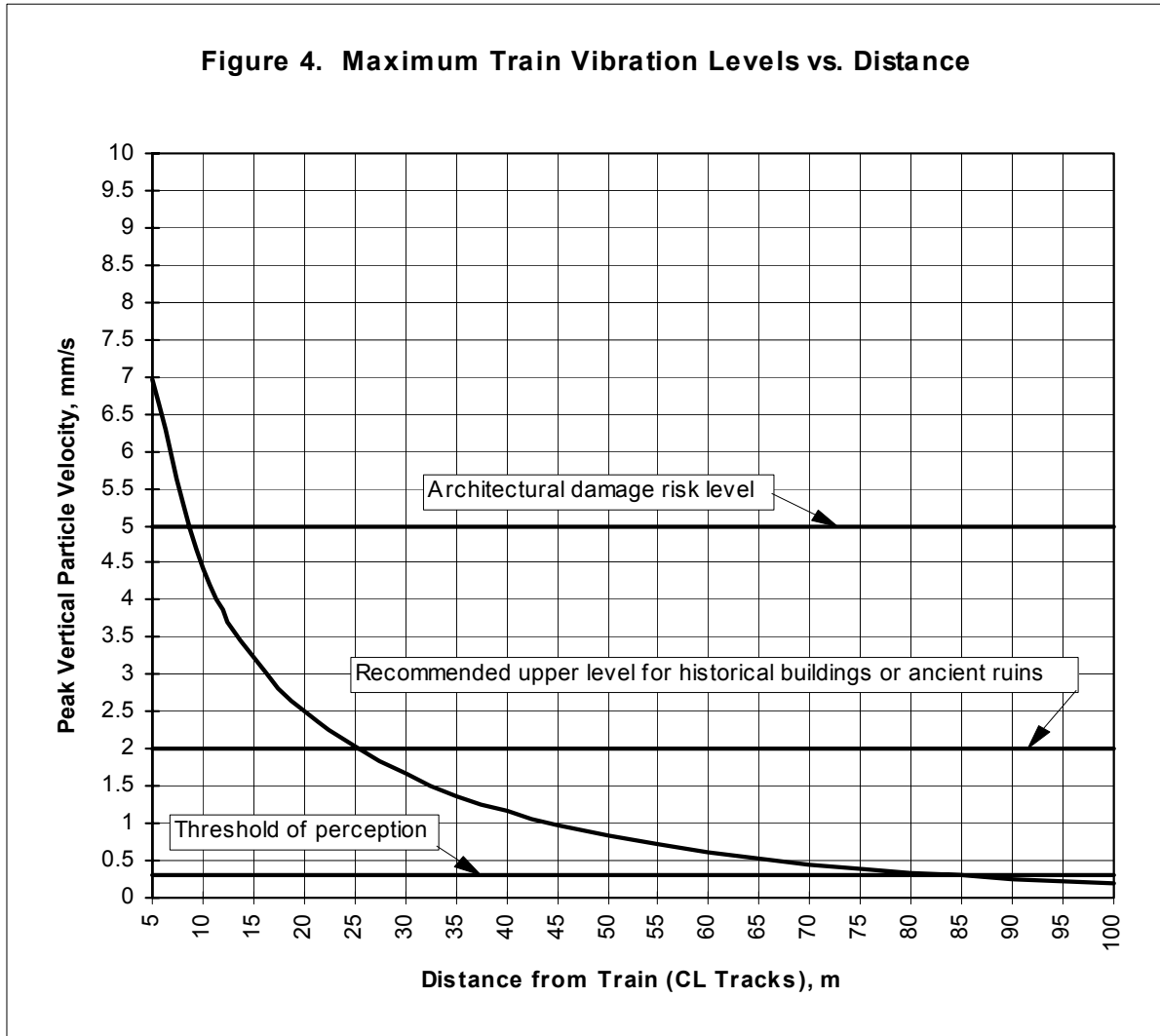


levels near the source than those in sandy soils. Vibrations in clay soils, however, tend to drop off more rapidly with distance than those in sandy soils.

Frequency ranges of construction vibrations, (including pile driving) tend to be the same as for traffic vibrations, mostly in the 10-30 Hz range, centered around 15 Hz, once in a while lower than 10 Hz, and rarely higher than 30 Hz.

Train Vibration Levels

Train vibration levels may be quite high, depending on the speeds, load, condition of track, and amount of ballast used to support the track. The highest train vibration measurement was 9.1 mm/s (0.36 in/sec) at 3 m (10 ft), in Sacramento. Using this information with the drop-off curve in Figure 1, we can construct a train vibration curve vs. distance. This is shown in Figure 4, beginning at 5 m (16 ft) where the vibration



level is calculated at 7 mm/s. The curve represents maximum expected levels from trains, and thus is very conservative. Measurements at various distances at other locations and different freight trains averaged about two-thirds of those shown in the curve.

Train vibrations tend to be in the same frequency ranges as traffic and construction vibrations. In some cases higher frequencies are encountered, especially in curves, caused by wheel chatter and squeal.

Impacts

Architectural and Structural Damage - The above discussions indicate that in any situation the probability of exceeding architectural damage risk levels for continuous vibrations from construction and trains is very low and from freeway traffic practically non-existent. However, if vibration concerns involve pavement breaking, extensive pile driving, or trains, 7.5 m (25 ft) or less from normal residences, buildings, or unreinforced structures, damage is a real possibility. This may also be true if these operations occur within 15 m – 30 m (50 ft- 100 ft) from historical buildings, buildings in poor condition, or buildings previously damaged in earthquakes.

Pile driving in close proximity (say within 3 m or 10 feet) of structures can cause additional problems, depending on the soils and configurations of substructures. An example was the reconstruction of San Francisco-Oakland Bay Bridge Toll Plaza in June 1987. A number of piles were driven in soft clay soils ("bay mud") close to the existing booth access tunnel underneath the freeway. Due to the large number of piles, and the proximity and configuration of the old substructure the lateral soil movement, caused by piles permanently displacing the clay, was resisted. The resulting conflict of forces was relieved by structure uplift and damage (cracks in the reinforced concrete tunnel).

Annoyance - As was discussed before, the annoyance level shown in Table 2 is highly subjective, and does not take into consideration elderly, retired, ill, and other individuals that may stay home more often than the "average" person. Nor does it account for people involved in vibration sensitive hobbies or activities, and people that like to relax in quiet surroundings without noticing vibrations. The threshold of perception, or roughly 0.25 mm/s (0.01in/sec) may be considered annoying by those people. Low level vibrations may also cause secondary vibrations and audible effects such as a slight rattling of doors, windows and dishes, resulting in additional annoyance. Annoying low frequency airborne noise can sometimes accompany earthborne vibrations.

Vibration Sensitive Operations - Aerospace and electronic laboratories, close tolerance manufacturing, calibration of sensitive instruments, radio & TV stations, etc. require additional attention. Shutting down their operations, even temporarily, could be extremely costly to the state. As was previously discussed vibration criteria for these operations are not well defined, for two main reasons. First, the operations are often classified and their precise nature is therefore not always known. Secondly, the

engineers involved in the critical operations often do not know how much vibration can be tolerated, or what operations they may be involved with in the future.

Heavy truck traffic on freeways within 30 m (100 ft), major construction within 60 m (200 ft), freight trains within 90 m (300 ft) and pile driving within 180 m (600 ft) may be potentially disruptive to sensitive operations.

Mitigation

Unlike with noise, there are no easy ways to mitigate earthborne vibrations. There are, however, a limited number of options available.

When designing new transportation facilities, reasonable amounts of care should be taken to keep these facilities away from vibration sensitive areas.

When dealing with existing transportation facilities, obvious vibration causes, such as pot holes, pavement cracks, differential settlement in bridge approaches or individual pavement slabs, etc., may be eliminated by resurfacing. In certain situations a ban of heavy trucks may be a feasible option.

The use of alternate construction methods and tools may reduce construction vibrations. Examples are predrilling of pile holes, avoiding cracking and seating methods for resurfacing concrete pavements near vibration sensitive areas, using rubber tired as opposed to tracked vehicles, placing haul roads away from vibration sensitive areas.

Scheduling construction activities (particularly pile driving) for times when it does not interfere with vibration sensitive operations (e.g. night time) may be another solution, especially in industrial areas.

Train vibrations may be reduced by using continuous, welded rails, vibration damping pads between rails and ties, and extra ballast.

Link With Historical Data

A considerable amount of effort has gone into the field measurements, reduction, documentation and reporting of vibration data since 1958. As data sets are accumulated with each vibration study, a more complete picture emerges of the generation and propagation of vibration waves under various conditions of geometry, soil, and source types.

Due to the lack of accurate prediction models for earthborne vibrations, empirical data is of utmost importance and can be used for future estimates when conditions are

alike. Historical data that can be linked to the present and future play a very important role in estimates and predictions of future vibrations.

Present and future personnel charged with the responsibility of performing vibration studies and maintaining vibration files should make every effort necessary to maintain a good correlation between any new and old instrument systems, calibration procedures, and measuring methods. The link between present and valuable historical data must be preserved.

Vibration Monitoring Equipment

During the period of 1958 - 1994 all of Caltrans vibration monitoring was performed by Translab. A transducer calibration system consisting of a shake table mounted on a concrete vibration isolation pad, and an Optron camera/amplifier system, measuring displacement allowed Translab its own transducers with traceability to the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS). Transducers were calibrated by mounting them on the shake table and running the latter at a known frequency and displacement.

Two types of sensors (transducers) were used by Caltrans. The first type was the **seismometer**. A seismometer measures vibrations at relatively low frequencies usually 1 - 200 Hertz (Hz), is very sensitive to low levels of vibrations and, through magnetic induction produces a voltage proportionally to velocity. It measures velocity directly via a signal conditioner, and is therefore called a velocity transducer. It is large, weighs about 7 kg (15 lbs), and, because of its mass, can be placed directly on the ground without further mounting attachments.

The second type of transducer was an **accelerometer**. As the name implies, this type of transducer measures acceleration directly. Used with an integrator it can also measure velocity and displacement.

The type of accelerometer used by Caltrans has a piezoelectric (pressure sensitive) crystal. As the transducer vibrates with the surface it is mounted on, acceleration changes the compression of the crystal, which in turn causes variations in the electrical charge across the crystal faces. These charge variations are proportional to acceleration.

An accelerometer is small, not as sensitive as the seismometer and has a wide frequency range, from 1 Hz to several KHz (1 KHz = 1000 Hz). Larger, more sensitive accelerometers, weighing about 1 lb, are available with a narrower frequency range from 0.1 Hz to 1KHz. Due to their small size and lack of mass, accelerometers should

not be placed directly on the ground, floor, or other vibrating surface without proper mounting. Accelerometers can be mounted various ways, depending on the surface.

For earthborne vibration work an accelerometer can be mounted via a magnet (supplied with it) to a block of steel of, say 5-10 kg (10-20 lbs). The steel block can then be placed directly on the ground, or other surface. The mass of the steel block provided adequate coupling of the accelerometer with the ground for the low frequency, low level vibrations generated by transportation facilities and construction.

Vibration Study Approach and Instrument Setup

Vibration studies can be classified into two main categories:

1. Studies involving existing transportation operations and facilities
2. Studies involving future transportation operations and facilities

Vibration Studies for Existing Construction Operations and Transportation Facilities -

These studies consist of mainly addressing vibration complaints due to existing traffic, or construction operations. Understandably, pile driving near homes or businesses will normally generate many noise and vibration complaints. Other construction operations can also be responsible. Traffic vibration complaints are often due to poor pavement conditions. Other reasons may be increases in traffic, heavy trucks, buses, etc. Sudden increases in traffic vibrations may be due to opening of new transportation facilities, or redirecting traffic.

Although complaints can originate from the entire spectrum of receptors, most are from residences, or businesses that have vibration sensitive equipment or operations.

The first step in investigating complaints should be interviewing the complainant(s). The screening procedures outlined later in this document cover the most important questions to ask. For the purposes of performing a vibration study, the most important issues are:

- The type and location of the vibration source(s)
- The complainant(s)' concerns, i.e., annoyance, damage, disruption of operations.
- The location that is most sensitive, or where vibrations are most noticeable.

Vibration monitoring of existing operations or facilities ranges from simple, single location measurements to more complex multi-instrument, simultaneous measurements. The former consists of taking measurements at the most sensitive location, or location perceived by the complainant to have the worst vibrations. The latter usually involves placing a sensor close to the source as a reference, and one or more sensors at the critical location(s) ("response sensors"). Simultaneous measurements will then positively identify the vibration source, the drop-off and the response (vibration level) at the location(s) of interest. The reference sensor remains

fixed in one location near the source, while the response sensor(s) may be moved to different locations.

Sufficient data should be collected for each location. For highway traffic vibrations, 10 passbys of heavy trucks (preferably worst case combinations of several trucks) for each location should be sufficient. For pile driving, at least one pile closest to the receptor should be monitored at each location of interest.

The highest vibration level at each location can then be compared to Caltrans or other appropriate criteria.

Vibration Studies for Future Construction Operations and Transportation Facilities -

Studies involving predictions of construction and operation vibrations of future transportation facilities often require vibration simulations to determine a site-specific drop-off curve. In order to generate vibrations that can still be measured at 60-90 m (200 to 300 ft) to develop the curve, the site must be free of high ambient vibrations (preferably less than 0.13 mm/s or 0.005 in/sec at the 90 m or 300 ft distance), and the generated vibrations must be relatively high. From Figure 1 we can calculate approximately how high the reference vibration V_0 at 5 m should be to detect the vibrations at 90 m. The V/V_0 ratio at that distance = 0.038; assuming we want V to be at least 0.13 mm/s; then $V_0 = 1/0.038 \times 0.13 = 3.4$ mm/s (0.13 in/sec). If a low-vibration site cannot be found, either the distance for the drop off curve must be shortened, or the reference vibrations increased. Caution must be used to apply the drop-off curve to pile driving projections, due to the previously discussed differences in propagation characteristics.

To generate data for the drop-off curve, a heavily-loaded water truck, or dump truck (preferably 25 tons or greater GVW) is run at high speed over 2" x 4", or 2" x 6" wooden boards. Normally, five boards are laid perpendicular to the direction of travel, and spaced 7.5 m (25 ft) apart along the direction of travel. The advantage of this arrangement is that the generated vibration "signature" is normally recognizable at 90 m (300 ft).

A minimum of two sensors must be used simultaneously: one reference sensor, and one or more response sensor. The reference sensor remains fixed at 5 m (16 ft) from centerline of travel, (or any convenient distance near the source) opposite the last board to be run over (most forward in line with the direction of travel). The response sensor(s) is (are) positioned at various distances away from the source. Because of the steepness of the curve near the source it is a good idea to cover shorter distance intervals near the

source and longer ones away from the source. To adequately cover the entire range of the drop-off curve, 6 to 8 locations must be monitored, and at least 5 truck passbys per location.

Frequently it is not possible to do the simulations on the site of interest, because of space limitations. Nearby empty lots or open fields, or data from other sites known or judged to have similar soil conditions can then be used.

Once the measurements have been made, the data at each location should be averaged. Using the reference location, and at least two others (including the furthest one), the soil parameter α can be calculated using equation 2. Ideally, the α value should remain constant for each location, but in reality it will vary. The average of several values can then be used to develop a drop-off curve. The vibration levels at all measured locations should then be plotted to determine how well they fit this curve. Assuming they fit reasonably well, a normalized drop-off curve using V/V_0 ratios and distances (similar to Figure 1) can then be developed and used with any source reference level, to predict the future level at any distance within the range of the curve.

If it is possible to do the simulations at the site, inside/outside building locations should be included to measure the building amplification or attenuation ratio.

The next step is to measure ambient levels at the site. Outside as well as inside building locations should be included for these measurements.

Using all the above information, future levels can be predicted and compared to existing ambient levels, Caltrans guidelines, or any other appropriate or required standard.

Concerns for vibrations of future transportation facilities are usually raised by vibration sensitive factories, laboratories, or other vibration sensitive sites. Unless construction activities are expected to occur very close to residential or other structures, or near historical buildings, these receptors are not routinely included in vibration studies for future facilities.

Vibration field studies including simulations are expensive. Unless the consequences of transportation and construction generated vibrations may be costly to Caltrans, the curves and techniques described in this document can be used to estimate "ball park" vibration levels, in lieu of field studies.

Vibration Reports

Each vibration field study should be documented in a report. Depending on the amount of sites measured, amount of data collected, methodologies used, and the importance of the study, the report may range from a simple one or two paged memo, to

a report of twenty or more pages long. A vibration study can be considered a mini-research project, and should contain enough information for the reader to independently come to the same conclusions.

As a norm, vibration reports contain the following topics, which will be described in greater detail:

- * Project title and description
- * Introduction
- * Objectives
- * Background
- * Study Approach
- * Instrumentation
- * Measurement Sites
- * Measurements
- * Data Reduction
- * Measurement Results
- * Data Analysis
- * Results and Comparison with Standards
- * Conclusions and Recommendations
- * Tables showing all measured data, summaries of results, analysis and standards
- * Figures showing site layouts and cross sections, instrument setups, drop-off curves, and other pertinent illustrations
- * References cited

In short, simple vibration studies, the topics may be described in a few sentences in a memo. In more complex studies, a fairly extensive report is usually required.

Project Title and Description - If the report consists of a short memo this info. can be put in the "Subject:" space. In a long report it should be put on a separate title page, with the date, who did the study (Div.or District, Branch, and personnel involved), and author of report.

Introduction - Typical opening sentences: "This report (memo) presents the results of a vibration study at The study was requested by, in response to concerns by that vibrations of would interfere withoperations. The study was performed by (branch or section) on (dates)."

Objectives - This is often combined with the introduction. Example: "The purpose of the study was to provide baseline data for estimating vibration levels in sensitive areas of Hughes Aircraft facility generated by construction and traffic of the proposed LA-105 Freeway."

Background - Used only when there is a long and complicated history connected with the reasons for the studies. Useful for documenting all the facts leading up to the study for litigation purposes. Dates first contacted, correspondence, actions taken, and

other pertinent details may be appropriate in this section. Not necessary in most studies.

Study Approach - May be combined with other sections. A short description of how the study was done. Example:

"First, vibrations generated by a 25 ton GVW three-axle water truck driven over five 2"x4" wooden boards were measured at various distances to measure the vibration attenuation with distance. This info. was then used to develop a drop-off curve....., etc." For simple studies, such as residential complaints: "The sensor was set up at four different locations where, according to the homeowner, vibrations were most noticeable. Five heavy truck passbys on Route were measured at each of the locations. ..."

Instrumentation - Always include description, manufacturer, model, serial no. of each vibration equipment components used. It is also extremely important to include the date instruments were last calibrated, by whom, where the records are on file, and whether calibration was traceable to the NIST (National Institute of Standards and Technology, formerly NBS). Essential in court cases!

Measurement Sites - Include a sketch, preferably to scale, of the relationship between source and measurement locations. Plot and number the sites on the sketch. Include typical cross sections if there are significant elevation differences between source and receptors. Plot significant structures. Show enough dimensions to pinpoint each measurement location. Show detailed descriptions, and instruments or sensors used at each location in the text, or in a separate table if there are many. Once locations are numbered and described, they can be referred to by number only.

Measurements - This section may also include the study approach. Basically explains the methods used, how sensors were mounted, number of measurements taken, what sources were measured (e.g. heavy trucks on Route 5), descriptor used and why, and other pertinent information concerning the vibration measurements. When possible, include a description of soil type and structure. This info. can often be extracted from nearby boring logs. Be sure to include ambient or background measurements.

Data Reduction - A short description of how the data was reduced can effectively be combined with the measurement section. Only if the reduction method is unusual or complex should it be discussed in a separate section.

Measurement Results - May also be combined with the measurement section. Briefly summarize data in the text by giving highest values, ranges, and averages. Should be

accompanied by a table summarizing measurement run No. (or just Run No.), date and time, measurement location, source (heavy truck in N/B lane No.4), distance, vibration level, dominant frequency, and optional remarks. This table may be put in the text or in an appendix with all other tables and figures. All individual measurements should be included as part of the report, for possible future use. Ambient or background vibration measurements can be expressed as a range of vibrations, typical frequency ranges, time period during which they were measured, and if possible the range of sources and distances.

Data Analysis - Developing drop-off curves, predicting future levels, calculating levels at specific distances not measured, etc. all should be in this section. May not be necessary for simple studies involving residential complaints, monitoring for compliance with a standard, or any other study involving vibration measurements only.

Results and Comparisons to Standards - Existing measured, projected, and predicted vibration levels and frequencies are summarized and compared to pertinent standards in this section. This is usually done in tabular form, and accompanied by Table 1, which shows the vibration criteria used by Caltrans.

Conclusions and Recommendations - Conclusions are drawn from the previous comparisons with standards. Typically for highway vibration complaints would be: "Although vibrations generated by heavy trucks on I-5 may at times be felt, they are far below the 'architectural damage risk level' criterion of 0.2 in/sec used by Caltrans."

Recommendations for mitigation are rather limited (see "Mitigation" section). However, in some cases strategies such as pile driving at night may solve interference with vibration sensitive manufacturing processes during day time. When ever possible, such recommendations should be included.

References - In complex reports, relying partly on previously gathered data, it may be beneficial to cite other reports or references by number. A listing of these references should then be included at the end of the report.

Field Review and Screening of Possible Vibration Problems

The following procedures were designed to screen vibration complaints near existing transportation facilities. They are intended to accomplish two things: 1) to evaluate the severity of the vibration problem, and 2) obtain preliminary information for a vibration study, should one be necessary.

The procedures are divided in two parts: problem definition and actions to take. An outline of the steps in each part follows:

I. Problem Definition

A. Interview resident at the site of concern. Ask the following questions:

1. What is the exact problem in the resident's opinion?

Many people confuse low frequency airborne noise with earthborne vibrations.

2. What are the sources in the resident's opinion?

Trucks on freeway?; city traffic?; trains? (sources may not be our jurisdiction.)

3. What are the specific concerns?

Annoyance?, interference with activities?, damage to the residence? If damage is the main concern, ask for evidence look for stucco cracks, cracks in driveways, walkways, walls, stucco, etc. Compare with other residences further away from the transportation facility. If these also have cracks, then it is safe to assume that the facility is not responsible.

4. Where are the vibrations most noticeable?

Which room?; which part of the yard? (Let resident point out the critical locations.)

5. What time of the day and/or what day of the week does the resident feel vibrations the most?

6. When did the resident become aware of the vibrations?

Try to correlate with changes in nearby traffic patterns, due to truck bans elsewhere, new industrial development, or other reason for truck increases.

B. Feel the vibrations

1. Stand at critical locations and try to feel vibrations when trucks pass by.

Place finger tips on furniture, walls, uncarpeted floor, ground outside the residence, patio floor, etc.

2. Have someone walk nearby; feel these vibrations and compare with the traffic vibrations. Also compare other in-house generated vibrations.

Walking, air conditioners, heater blowers, and garbage disposals, etc. often generate more vibrations than traffic.

3. Stand on freeway shoulder, sidewalk next to highway, or anywhere close to the suspect source. Feel vibrations and compare with those felt at the receptor.

Place finger tips on ground or pavement surface.

4. Look for obvious causes of excessive vibrations.

Pot holes, pavement joints, sag, and pavement cracks, or anything that could cause above normal vibrations; also look for drainage or other structures transmitting vibrations to the receptor without benefit of soil attenuation.

C. Evaluate severity of the problem.

The graphs in Figures 1 - 4 show typical vibration attenuations with distance for various sources. Use these to evaluate typical relationships of near and far source vibration levels. If vibrations appear to dropoff at a significantly lesser rate, then suspect that something unusual is going on. For instance, vibrations

may be transmitted by underground structures, which can cause problems at the receptor.

1. If vibrations feel as strong (or almost as strong) at the receptor as they do near the source (such as on a freeway shoulder), consider problem severe.
2. If vibrations at the receptor are readily noticeable and appear to interfere with activities or vibration sensitive operations, consider problem severe.
3. If vibrations of any amplitude are an issue in litigation, consider the problem severe.
4. If after this screening procedure uncertainty still exists, consider problem severe.

II. Actions To Take

A. If problem is not severe:

1. If there are obvious causes for excessive vibrations, such as pot holes, etc., contact Maintenance or other departments and find out if scheduled for repair or resurfacing.
2. Write memo to resident explaining your findings.

If there are obvious solutions such as patching or resurfacing, tell the resident. If there are no obvious solutions, explain to the resident that although vibrations may be felt, they are not damaging. Use background info. in this document.

B. If problem is considered severe, or if the resident keeps insisting on actual monitoring, consider contracting out vibration monitoring or a complete vibration study.

APPENDIX

BASIC VIBRATION FORMULAE

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APPENDIX

BASIC VIBRATION FORMULAE

Symbols

- A = Zero-to-Peak, or Peak Acceleration (Units: m/sec², mm/sec², ft/sec², in/sec²)
- A_g = Zero-to-Peak, or Peak Acceleration (Units: "g" = acceleration of gravity), where:
- 1 g = 9.807 m/sec²
 = 9807 mm/sec²
 = 32.174 ft/sec²
 = 386.102 in/sec²
- D = Peak-to-Peak Displacement (Units: m, mm, ft, in) (Normally of interest)
- D/2 = Zero-to-Peak, or Peak Displacement (Units: m, mm, ft, in)
- f = Frequency (Units: Hertz)
- V = Zero-to-Peak, or Peak Particle Velocity (Units: m/sec, mm/sec, in/sec)
- π = 3.14159 etc.....

Formulae for Sinusoidal Waves

Units need to be consistent; for example, if D is in mm, then V must be in mm/sec, and A either in mm/sec² or units of "g" (9807 mm/sec²).

With **displacement**, we are normally interested in the peak-to-peak value or in other words, the total displacement (distance between the + peak and - peak) soil particles travel. Sometimes, however we may also be interested in the zero-to-peak displacement, or displacement relative to a stationary (zero) reference position. For sinusoidal waves, the + side of reference and the - side are symmetrical, and zero-to-peak values are D/2.

With **velocity** and **acceleration**, however, we are always interested in the zero-to-peak values. These give an indication of maximum value, without regard of the direction.

Acceleration is most commonly used in units of **g**.

Following are formulae expressing the relationships between displacement, velocity, and acceleration for sinusoidal vibration waves.

Velocity and Displacement:

$$V = 2 \pi f(D/2) \quad (\text{Eq.A-1})$$

$$V = \pi fD \quad (\text{Eq.A-2})$$

$$D/2 = V/(2 \pi f) \quad (\text{Eq.A-3})$$

$$D = V/(\pi f) \quad (\text{Eq.A-4})$$

Acceleration and Displacement:

$$A = (2 \pi f)^2(D/2) \quad (\text{Eq.A-5})$$

$$A = 2 \pi^2 f^2 D \quad (\text{Eq.A-6})$$

$$A_g = (2 \pi^2 f^2 D)/g \quad (\text{Eq.A-7})$$

If D is in inches:

$$A_g = (2 \pi^2 f^2 D)/386.102 = 0.0511 f^2 D \quad (\text{Eq.A-8})$$

If D is in mm:

$$A_g = (2 \pi^2 f^2 D)/9807 = 0.00201 f^2 D \quad (\text{Eq.A-9})$$

Acceleration and Velocity:

$$A = 2 \pi fV \quad (\text{Eq.A-10})$$

$$A_g = (2 \pi fV)/g \quad (\text{Eq.A-11})$$

If V is in inches per second:

$$A_g = (2 \pi fV)/386.102 = 0.0163 fV \quad (\text{Eq.A-12})$$

If V is in mm per second:

$$A_g = (2 \pi fV)/9807 = 0.000641 fV \quad (\text{Eq.A-13})$$

Acceleration or Velocity in Decibels:

$$A(\text{dB}) = 20 \text{Log}(A/A_0); V(\text{dB}) = 20 \text{Log}(V/V_0) \quad (\text{Eq.A-14})$$

where A = acceleration, A_0 = reference acceleration,

V = velocity, and V_0 = reference velocity (units must be consistent)